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The effects of age, interface modality, and system design on drivers' attentional demand when making phone calls while driving on a limited-access highway

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ABSTRACT

In-vehicle information systems that allow drivers to use a single voice command to complete a task rather than multiple commands better keep drivers' attention toward the road, especially compared with when drivers complete the task manually. However, single voice commands are longer and more complex and may be difficult for older drivers to use. The current study examined the glance behavior, workload, and driving performance of drivers age 20–66 years when they placed a call using their hands or voice with the Chevrolet MyLink or Volvo Sensus information system during highway driving. In general, as age increased, drivers took longer to complete phone calls, reported greater workload when using voice commands, and made significantly more off-road glances lasting longer than two seconds when placing calls relative to younger drivers. Both the voice-command systems of MyLink and Sensus increased the proportion of time that drivers were looking at the road when calling compared with manual phone calling, but the relative increase was greater when using MyLink's single-voice-command system compared with the multiple-command system of Sensus, and this advantage grew as drivers aged. The findings indicate that placing calls while driving using voice commands helps drivers of all ages keep their attention toward the road better than doing so manually, and that, contrary to expectation, using a single-command system like MyLink's worked better than a multiple-command system like Sensus for older drivers as well as younger ones.

1. Introduction

The National Motor Vehicle Crash Causation Study indicates that in-vehicle distractions were the critical reason leading to 11 percent of towaway crashes (NHTSA, 2008). Drivers engage in many distracted driving behaviors (Farmer, Klauer, McClafferty, & Guo, 2015; Kidd, Tison, Chaudhary, McCartt, & Casanova-Powell, 2015), but most current efforts to understand crash risk from secondary task engagement center on electronic device use. Controlled experimental studies show cellphone use while driving degrades aspects of driving performance such as hazard detection and reaction time compared with "just driving" (e.g., Atchley, Tran, & Salehinejad, 2017; Caird, Willness, Steel, & Scialfa, 2008; McCartt, Hellinga, & Braitman, 2006). Naturalistic driving and epidemiological studies have found increased crash risk associated with engagement in cellphone use (Guo et al., 2016; Kidd & McCartt, 2015; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006; McEvoy et al., 2005),

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especially visual-manual phone use that takes the driver's eyes away from the road (Guo et al., 2016; Klauer et al., 2006). Furthermore, visual-manual cellphone tasks such as dialing, texting, looking at, or reaching for the device increase crash risk the most for drivers under 30 years old and over 65 years old relative to middle-age drivers (Guo et al., 2016).

To reduce distraction from visual-manual interactions with cellphones and other electronics embedded in the vehicle, automakers are introducing systems that allow drivers to use voice commands to interact with connected cellphones and vehicle systems instead of traditional visual-manual interfaces. However, the design of voice interfaces in modern vehicles varies, along with their success in reducing visual demand relative to visual-manual interfaces. Reagan and Kidd (2013) examined four production embedded systems using task analysis and found design approaches varied from a "one-shot" approach where drivers could perform a task using a single compound voice command to systems that required a layered series of commands to navigate through menus and submenus in the system. In an on-road driving experiment, Mehler et al. (2016) compared these two disparate design approaches and had drivers call a contact stored in a connected smartphone using voice commands or the systems' visual-manual interfaces. The voice interfaces of both embedded systems reduced but did not eliminate visual demand relative to the visual-manual interfaces, but the one-shot approach reduced visual demand significantly more than the multistep menu-based approach.

However, the reductions in visual demand provided by voice interfaces may not be observed for all drivers. Consistent with work to understand age-related declines in cognitive function (e.g., general slowing (Salthouse, 1996), reduced working memory capacity (Bopp & Verhaeghen, 2005), and executive functioning (Kramer, Hahn, & Gopher, 1999), applied research has identified significant increases in attentional demand for older relative to younger participants in simulator and field studies where drivers completed different in-vehicle secondary tasks while driving (Lee et al., 2015; McWilliams, Reimer, Mehler, Dobres, & Coughlin, 2015; Tijerina, Johnston, Parmer, Winterbottom, & Goodman, 2000; Tsimhoni, Smith, & Green, 2002; Wikman & Summala, 2005). Lee et al. reported that older drivers' manual radio tuning was associated with longer mean glance durations to the radio, more total glances, and longer total glance duration relative to younger drivers.

Among researchers who studied the effects of age and secondary task input modality, the use of voice interfaces reduced (McWilliams, et al., 2015; Tsimhoni et al., 2002; Wikman & Summala, 2005) or in some cases eliminated (Tijerina et al., 2000) age differences. Tijerina and colleagues' test track study compared attentional demands when entering addresses into four production navigation systems using visual-manual input (3 of the 4 systems) or voice input (1 of the 4 systems). Task completion times for older drivers were twice as long as younger drivers when collapsing across the devices. However, a comparison of individual devices showed task completion times for younger and older drivers were essentially equal for the voice recognition system. The same relationships between driver age group and navigation system were reported for the average number of seconds drivers' eyes were off the forward road. For all drivers, mean glances to the road ahead were approximately 3–4 times longer when using the voice-based system. In contrast, McWilliams et al. (2015), Tsimhoni et al. (2002), and Wikman and Summala (2005) reported consistent increases in attentional demand with increased age for visual-manual and voice-based secondary tasks, although the magnitude of the age differences were smaller when completing tasks that required voice input. Across these studies, indices of attentional demand sensitive to the age-related changes include, but are not limited to, task completion time; mean duration of a single glance (to the road, away from the road, or to display/device); total glance time (away from the road, or to in-vehicle display/device), off-road glances longer than 2 s, self-reported workload, and measures of lateral vehicle control.

Interestingly, Tijerina et al. (2000) reported significant differences by device/interaction type for mean single on-road glance durations in addition to the more commonly reported off-road glance measures, but they did not report a breakdown of the former data by age group. Recent work examining naturalistic driving datasets indicates that the way on-road and off-road glances are distributed during a secondary task is associated with crash risk (Seaman et al., 2017; Seppelt et al., 2017). For example, Seppelt et al. (2017) found that mean off-road single glance duration was not significantly different for crash and near-crash events in the 100-car naturalistic dataset. However, mean single on-road glance duration was significantly longer in near crash events than in crash events. Consequently, further consideration of on-road glance measures in addition to off-road measures seems warranted.

It would be useful to know whether different approaches to interface design implemented in embedded systems of modern production vehicles reduce attentional demand for younger or older drivers in a similar or a differential fashion as little data currently exist. As mentioned above, research indicates increased risk of crashes associated with visual-manual distraction for younger and older drivers relative to middle aged drivers (e.g., Guo et al., 2016). Further, it is likely that middle-aged and older drivers have more exposure to embedded infotainment systems given their preference for luxury models that tend to feature embedded infotainment systems (Highway Loss Data Institute, 2014) and the association between increased earnings and age (Bureau of Labor Statistics, 2018) that suggests older drivers may be more able to afford optional technology packages than younger adults. The current study analyzed whether multiple measures of attentional demand varied as a function of age, interface design, or input modality when drivers negotiated free-flowing interstate traffic and used voice and visual-manual interfaces of two embedded infotainment systems to place phone calls to contacts saved in a smartphone contact list.

2. Method

Data for the current study were collected during an on-road experiment that evaluated driver use of two infotainment systems, Chevrolet MyLink and Volvo Sensus, voice and visual-manual interfaces to each other (Mehler et al., 2016), and to a smartphone (Reimer, Mehler, Reagan, Kidd, & Dobres, 2016) to place phone calls and complete other secondary tasks, such as entering addresses for navigation while drivers negotiated free-flowing interstate traffic. For the current study, only the phone- contact calling tasks with the voice and visual-manual interfaces of each embedded system were considered. This permitted a focused analysis to assess whether input modality and the design approaches of the two embedded systems affected measures of eye glance behavior, vehicle control, subjective workload, and secondary task performance differently for drivers of different ages. The navigation task was not analyzed because it was not completed using a visual-manual interface. Data from trials where the smartphone was used to complete the tasks were excluded to avoid obscuring the goal of studying whether underlying design approaches of embedded systems might moderate effects of age. Despite their exclusion, treatment of the smartphone condition and navigation tasks are referenced below to fully describe the experimental procedure.

2.1. Participants

The analysis sample consisted of 80 participants who ranged in age from 20 to 66 (M = 40.3, SD = 15.6), 20 each from four age groups (18–24, 25–39, 40–54, 55–69) per the National Highway Traffic Safety Administration (NHTSA) guidelines for testing the distraction potential of embedded visual-manual systems (NHTSA, 2013). Males and females were distributed evenly within each age group. Recruitment screening led to a sample of drivers who reported they held a driver's license for at least three years, drove three or more trips per week, and were in good health. Prospective participants were excluded if they reported taking medications that caused impairment, serious medical conditions (e.g., a history of stroke), or being in a police-reported crash in the preceding six-month period. Institutional review of the experimental protocol was provided by the Massachusetts Institute of Technology. Participants received $75 for participation.

An initial 122 drivers completed screening and were recruited to participate in the study, and 42 were excluded from analysis. Six participated during the development of the research; two were excluded due to deviations from the research protocol; four were excluded due to equipment failure; one participant who failed to meet study criteria after closer review; three cases were excluded because of voice recognition problems with a voice interface; four were excluded due to unsafe or irregular roadway conditions (e.g., heavy traffic, weather) during their drives; one was excluded due to personal hygiene issues; and nine participants were excluded as residuals after it was confirmed that full data sets were obtained from the targeted sample of 80 participants. In addition to the screening questions designed to ensure fitness for driving, research assistants terminated data collection for 10 drivers due to safety concerns (one driver could not complete secondary tasks while driving; five exhibited unsafe driving behaviors to the research assistant early in the drive; and four drivers could not learn secondary tasks during the training period) Additionally, two drivers declined to participate after the training phase because they did not feel comfortable performing the tasks while driving.

2.2. Vehicles and embedded systems

A 2013 Chevrolet Equinox and 2013 Volvo XC60, both SUVs, were used in the on-road driving experiment. The vehicles were instrumented with a forward-facing camera that captured scenes of the road ahead at 30 Hz, a driver-facing camera recording at 30 Hz to support the coding of eye glance behavior, and other cameras capturing interactions with the vehicle controls and the rearward roadway scene at 15 Hz. A microphone provided a full audio record of participants' trials. Vehicle speed was captured from a Garmin 18X global positioning system (GPS), and steering inputs were recorded from each vehicle's controller area network (CAN) bus.

The Volvo Sensus voice interface in the 2013 XC60 required drivers to navigate multiple menus and confirm prior commands as they progressed through the task of calling a contact stored on a connected cellphone. For example, to call a contact with the Sensus voice interface, a driver pressed the voice button on the steering wheel to initiate the task, then waited for a beep that indicated the system was ready. They then proceeded through the following sequence of voice commands and system responses: (1) driver said "phone, call contact", (2) system prompted "name please", (3) driver said "John Smith", (4) system prompted "say line number", (5) driver said "one", (6) system prompted "call John Smith at home, confirm yes or no", (7) driver said "yes" and then the call was initiated. The Sensus always asked the driver to identify a line number even when a contact only had one number.

To complete the same task using Chevrolet MyLink's voice interface in the 2013 Equinox, the driver first engaged the system by pressing the voice command button on the steering wheel. After receiving a beep indicating the system was ready, the driver said, "call John Smith." The system then confirmed, "calling John Smith" and placed the phone call. For contacts associated with multiple phone numbers, the driver specified the type of phone number to ensure the proper line was selected (e.g., "Call John Smith at home).

Sensus required fewer steps to select a phone number with its visual-manual interface than MyLink's visual-manual interface. With the Sensus, the driver used a rotary knob to scroll through the full contact list before selecting the target name and phone number, whereas MyLink required drivers to navigate through several system menus, starting with selecting the alpha-numeric bin (e.g., ABC, DEF) corresponding to the contact's last name and then searching a shortened list of contacts in the bin. Table 1, adapted from Reagan and Kidd (2013), provides the number of steps and the processing modalities required to call a contact using the voice and visual-manual interfaces for each system.

Table 1
Steps and processing modalities needed to call a contact using the Sensus and MyLink voice and visual-manual interfaces (from Reagan and Kidd, 2013).

System	Voice interface	Visual-manual interface
Sensus	7 (3 visual-manual, 4 voice)	3 visual-manual
MyLink	3 (1 visual-manual, 2 voice)	7 visual-manual

2.3. Cellphone directory structure

A phone directory with 108 stored contacts was created and loaded into a Samsung Galaxy S4 smartphone, which was paired to each study vehicle using Bluetooth. The list of 108 contacts was distributed evenly so that there were 18 contacts in six alphanumeric bins consistent with the way MyLink organized contacts (e.g., ABC, DEF). Contacts were associated with either a single phone number or two phone numbers.

2.4. Procedure

Half of the 80 participants drove the Volvo XC60 and used the Sensus, and half drove the Chevrolet Equinox and used MyLink; even gender and age distributions were present across each vehicle. Upon arriving at the MIT AgeLab, participants read and provided informed consent and were screened a second time for fitness to drive a vehicle in the study. Participants then completed a survey to collect demographic data and information about driving attitudes and technology experience. Electrodes for collecting various physiological measures were then applied (see Mehler et al., 2016), and participants were instructed how to complete the subjective workload rating scale administered during the experiment.

Participants were taken to the test vehicle in a nearby parking lot for training and familiarization. In the parking lot, drivers received an overview of their assigned vehicle (e.g., how to adjust seat, mirrors, steering wheel, heating and cooling, select gears). Participants reversed the vehicle out of the parking space and then pulled forward back into the space to become familiar with the vehicle; they were then encouraged again to adjust the seat, mirrors, etc. as needed for comfortable and safe operation. Training instructions (and experimental prompts) were provided by prerecorded audio prompts initiated by a research associate who remained in the back seat of the vehicle throughout the experiment. Through the training, research associates answered questions and provided further instructions where needed. Participants were trained how to complete a phone contact calling task using the visual-manual and voice interfaces and destination entry task using the voice interface of either the embedded system (i.e. MyLink or Sensus) or smartphone, depending on which technology was being used during the first half of the experimental drive. Participants were trained to complete the visual-manual phone contact calling task using rotary knob/push button controls in the vehicle's center stack but were not prevented from discovering alternative ways to complete the task during the experimental drive. Participants who discovered alternative methods were permitted to use them. Next, participants were trained on how to place phone calls using the voice interface. Drivers were instructed about short-cut voice commands, and those assigned to use Sensus completed a voice calibration process. MyLink did not have voice calibration. Participants practiced the phone contact calling task with the visual-manual and voice interfaces until they demonstrated they could complete the tasks and indicated they were ready to progress. Throughout the procedure, participants were instructed that safe driving was their top priority and that they should ignore instructions to engage in a secondary task if they were not comfortable. Average training time was 20 min.

The experimental driving route began and ended at the Massachusetts Institute of Technology (MIT) campus in the Boston area. Throughout the drive the research assistant seated in the rear of the vehicle monitored recording equipment, triggered prompts based upon a set protocol (e.g. after the driver responds to task A press a key to start a defined lead up to task B), and monitored participants' performance to ensure safe driving and adherence to the protocol. Upon leaving MIT, drivers proceeded on local roads to interstate I-93 north out of the city to interstate I-495 south. This segment of the drive took approximately 30 min and served as an adaptation period to the vehicle for the driver. The first set of task trials began on I-495 south. Interstate 495 was a divided interstate with three 15-foot wide lanes in each direction and a posted speed limit of 65 mph. As in training, trial instruction and task stimuli were administered using prerecorded audio. Participants completed one block of phone contact calling task trials using the visual-manual interface, and one block of phone contact calling task trials using the voice interface while driving on I-495 south. The order of visual-manual and voice phone contact calling task trial blocks was counterbalanced across the first and second half of the experimental drive across participants. Each phone contact calling task block included four trials. The first two phone contact calls placed were to contacts associated with a single phone number, and the second two were to contacts associated with two phone numbers (e.g. home and work). The two phone contact calling task blocks were separated by a block of three destination entry trials where participants used voice commands to enter a destination. There was a three-minute break between each block of phone contact calling or destination entry task trials.

Participants stopped at a rest area after completing the first half of the experimental drive. At the rest area, participants completed the self-reported workload scale for each block of tasks. Then they were trained on how to complete the same tasks using the other technology, either the smartphone or embedded system. Participants completed the same tasks during the return trip on I-495 north. At the end of the experimental drive, participants completed the self-reported workload scale for the tasks completed in the second half of the drive and a postdrive questionnaire. Participants took approximately 4 h to complete the study.

2.5. Dependent measures

The dependent variables analyzed for the current study included self-reported workload, task completion time, measures of visual demand when calling a contact, and driving performance measures. Self-reported workload was measured by asking drivers to rate workload for the voice and visual-manual contact calling tasks on an 11-point labeled Likert scale of 0 ("low") to 10 ("high") that included unlabeled inter-point responses (e.g. 21 possible values). Workload was described to participants as being a construct unique to the individual who completed the task and may require mental effort, attentional demand, physical effort, time pressure, distraction, or frustration. Participants rated the voice and visual-manual phone contact calling tasks and the address entry task on a single-page form that had a scale for the three tasks to permit drivers to rate each task with respect to the others. Task completion time was defined as the number of seconds it took to complete phone contact calling, beginning at the end of the prerecorded audio prompt to start a task and ending after the participant successfully or unsuccessfully completed the task. The timing and location of glances were coded by two research associates separately and mediated by a third researcher when discrepancies arose (see Reimer, Mehler, Dobres, & Coughlin, 2013 Appendix G for a detailed description of procedures). Glance duration was defined as the time from the first video frame where the driver initiates gaze to a new location to the last video frame before the eye moved to a new location (following ISO, 2001, 2002). Steering wheel reversal rate defined as an angular reversal gap greater than 3° per minute was recorded from each vehicle's CAN-bus as a measure of lateral control. Mehler et al. (2016) integrate a discussion of the theoretical and empirical bases for the selection and use of the measures analyzed here.

2.6. Analysis plan

Statistical analyses were conducted using SAS 9.4. Separate linear mixed models were constructed using the MIXED procedure to examine the percentage of glance time to the forward road, mean duration of single glance to the forward road, percentage of off-road glances greater than 2 s, task completion time, self-reported workload, and steering wheel reversals per minute. Previous research indicated these measures are sensitive to changes in driver attentional demand associated with interface modality and age (Lee et al., 2015; McWilliams et al., 2015; Tijerina et al., 2000; Tsimhoni et al., 2002; Wikman & Summala, 2005).

Each dependent measure was modeled with the main effects of driver age as a continuous variable; system implementation (Volvo Sensus, Chevrolet MyLink); and interface modality (voice, visual-manual); the two-way interactions between driver age and system implementation and interaction between driver age and interface modality; and three-way interaction between driver age, system implementation, and interface modality. Driver was included as a random effect in each model to account for multiple observations from each participant. Type III F tests of each effect in the linear mixed model were used to identify those which significantly contributed to the explanation of variance in each dependent measure at the 0.05 level. Estimates from the linear mixed model were used to interpret significant main effects of driver age and significant interactions between driver age and other fixed effects. The results for the main effects of system implementation, interface modality, and the interaction between these variables are not discussed since these results are discussed in Mehler et al. (2016).

The complexity of the phone contact calling task varied. Participants always made two calls to contacts with one phone number (i.e., easy), followed by two calls to contacts with two phone numbers (i.e., hard). Preliminary analyses in the current study included the interaction between complexity (easy, hard) and driver age, but the interaction did not significantly contribute to the explanation of any dependent measures. Thus, the main effect of complexity and interaction between complexity and driver age were not included in the final models.

In addition to the linear mixed models, descriptive analyses of phone contact calling were conducted to describe the severity (i.e., attempting but failing to complete phone contact calling task) and source of errors (i.e., error by user versus system) across the sampled age groups (see Mehler et al., 2016 for a detailed discussion of error coding). Descriptive statistics collected during the prescreening procedure are included to describe self-reported driving exposure, formal education received, and attitudes about technology across the sampled age groups.

3. Results

3.1. Sample characteristics and task completion accuracy

Among the 76 drivers who provided estimates of mileage driven in the prior year, 82 percent reported driving in or above the range of 5001–10,000 miles (71 percent among 20–24-year-old participants, 79 percent among 25–39-year-old, 85 percent among 40–54-year-old participants, 90 percent among participants aged 55 and older). Formal education received was slightly lower for the youngest age group ($M = 3.8$) than the older groups ($M_{25-39} = 4.7$, $M_{40-54} = 4.5$ $M_{55+} = 4.7$), with values of 3, 4, and 5 indicating some college, college graduate, and some graduate school, respectively. Experience with and trust in technology were measured by single questions that used 10-point Likert scales with 1 indicating very inexperienced/distrustful and 10 indicating very experienced/trustful. Mean ratings for these items were similar across the age groups: experience with technology ($M_{20\text{–}24}$ = 8.6, $M_{25\text{–}39}$ = 8.8, $M_{40\text{–}54}$ = 8.2 M_{55+} = 8.3) and trust in technology ($M_{20\text{–}24}$ = 7.9, $M_{25\text{–}39}$ = 7.8, $M_{40\text{–}54}$ = 7.6 M_{55+} = 7.7).

Participants' ability to successfully complete the phone contact calling tasks was considered. There were 640 phone contact calling task trials across the sample and interface modalities. Ninety-three percent of phone contact call attempts occurred without error. Participants failed in their attempt to complete a call in six trials (1%). In the remaining 6% of trials, attempts were categorized as completed successfully but an error occurred during the attempt. In these trials, participants backtracked to a previous step or received a prompt by the research associate before completing the phone contact calling task. Across age groups, error-free trials were highest for 20–24-year-old participants (98%) and lowest for 55–66 year-olds (88%). The percentage of error-free trials ranged from 90% to 96% across the four system and interface combinations (MyLink visual-manual, 96%, MyLink voice, 92%, Sensus visual-manual, 90%, and Sensus voice, 93%).

Errors were classified as being caused by the user, such as when drivers selected the wrong button or issued an incorrect or mistimed voice command, or caused by the system, such as when the driver issued a timely, clearly spoken command that the system failed to process. Table 2 provides the percentage of trials that were error-free, involved a user error, or involved a system error by age group.

3.2. Mixed modeling results

3.2.1. Percentage of total glance time to the forward road

There was a significant effect of age and a significant interaction between age, interface modality and system implementation on the percentage of total glance time to the forward road. The interaction between age and system implementation and interaction between age and modality were not significant (Table 3). In general, there was a 1.1 percentage point decrease in the percentage of glance time to the forward road per 10-year increase in age. Placing calls using MyLink's voice system was associated with a significantly greater percentage of total glance time to the forward road (M = 86.05, SD = 7.17) than the other interface and modality combinations (Sensus voice interface, M = 73.78, SD = 9.60; MyLink visual-manual 48.35, SD = 10.9; Sensus visual-manual 50.29, SD = 10.25); however, the difference in the percentage of time drivers looked at the forward roadway when using the voice interface relative to the visual-manual interface differed as a function of driver age between MyLink and Sensus. The percentage of total glance time to the forward road decreased less than half a percentage point for each 10-year increase in driver age when drivers used the MyLink voice interface to place calls ($\beta = -0.43$), but decreased 3 percentage points more per 10-year increase in driver age when using MyLink's visual-manual interface ($\beta = -3.1$) (Fig. 1). In contrast, after holding all other variables constant, the percentage of time drivers looked at the forward roadway decreased 2.5 percentage points for every 10-year increase in driver age when calls were placed with Sensus' voice interface but only 1.2 percentage points when using Sensus' visual-manual interface.

Table 2
Percentage of phone contact calling trials (N = 640) with no errors, user errors, or system errors by driver age group.

Age group	Error-free	User-error	System-error
20–24	97.5	2.5	0
25–39	93.1	6.3	0.6
40–54	91.9	6.9	1.3
55–66	88.1	9.4	2.5
Total	92.7	6.3	1.1

Table 3
Summary of main effect of age and interactions of age with system implementation and interface modality.

Dependent Measure (variable in data)	Type III *F*-test			
	Age	Age × System	Age × Modality	Age × Modality × System
Percentage of total glance time to the forward road	$F(1, 76) = 9.91$, $p = 0.01$	$F(1, 76) = 0.00$, $p = 0.94$	$F(1, 556) = 2.27$, $p = 0.13$	$F(1, 556) = 22.29$, $p < 0.001$
Mean duration of single glance to forward road	$F(1, 76) = 0.17$, $p = 0.68$	$F(1, 76) = 4.46$, $p = 0.04$	$F(1, 556) = 2.72$, $p = 0.10$	$F(1, 556) = 21.96$, $p < 0.001$
Percentage of glances off the forward roadway that were longer than 2 s	$F(1, 76) = 4.84$, $p = 0.03$	$F(1, 76) = 0.44$, $p = 0.51$	$F(1, 556) = 2.55$, $p = 0.11$	$F(1, 556) = 2.08$, $p = 0.15$
Self-reported workload	$F(1, 75) = 0.98$, $p = 0.33$	$F(1, 75) = 0.08$, $p = 0.77$	$F(1, 232) = 4.06$, $p = 0.05$	$F(1, 232) = 5.23$, $p = 0.02$
Task completion time	$F(1, 76) = 32.34$, $p < 0.001$	$F(1, 76) = 0.09$, $p = 0.77$	$F(1, 556) = 0.26$, $p = 0.61$	$F(1, 556) = 3.46$, $p = 0.06$
Steering wheel reversals per minute	$F(1, 76) = 0.64$, $p = 0.43$	$F(1, 76) = 0.43$, $p = 0.51$	$F(1, 553) = 7.32$, $p = 0.007$	$F(1, 553) = 2.07$, $p = 0.15$

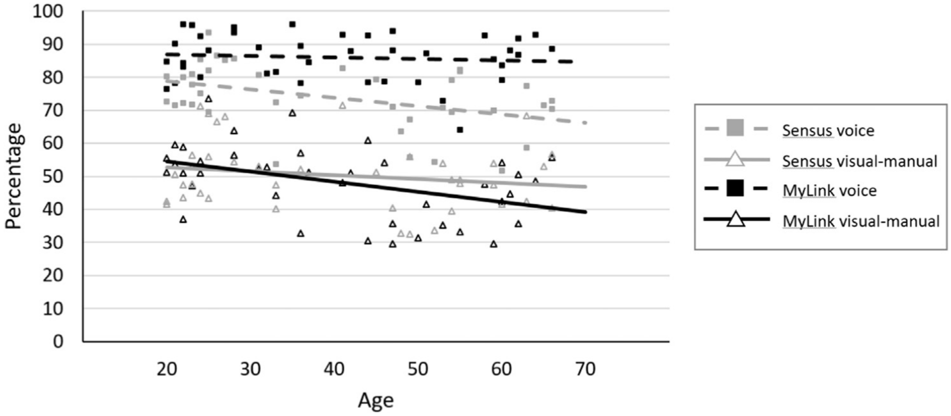

Fig. 1. Percentage of glance time to forward road when phone contact calling by age, interface modality, and system implementation. Lines of best fit indicate simple effects of age for each interface modality-system implementation condition. Points reflect a participant's percentage of glance time to the forward road averaged across four phone calling tasks for each modality-system condition.

3.2.2. Mean duration of a single glance to the forward road

The interaction between age and system implementation and interaction between age, interface modality, and system implementation on the mean duration of single glances to the forward road were statistically significant (Table 3). Overall, average single glance duration to the forward road was longer with the two voice interfaces (MyLink: $M = 4.25$, SD = 2.11; Sensus: $M = 2.59$, SD = 1.19), compared with the two visual-manual interfaces (MyLink: $M = 0.86$, SD = 0.32; Sensus: $M = 0.97$, SD = 0.33). However, the relative difference in the average duration of glances to the forward road when drivers used the voice interface versus the visual-manual interface differed between systems by driver age (Fig. 2). The mean duration of a single glance to the road changed little per 10-year increase in driver age when either visual-manual interface was used to place calls (MyLink: $\beta = -0.06$, Sensus: $\beta = 0.00$), but the mean duration of a single glance to the road increased 0.4 s per 10 years of age when drivers placed a call using MyLink's voice interface but decreased at a rate of 0.2 s per 10 years of age when using Sensus' voice system. The main effect of age and interaction between age and modality on the mean duration of single glances to the forward road were not significant.

3.2.3. Percentage of glances off the forward roadway longer than 2 s

The main effect of age on the percentage of glances off the forward roadway that were longer than 2 s during the contact calling task was statistically significant (Table 3). The average percentage of glances off the forward roadway greater than 2 s when drivers were calling a contact increased 0.4 percentage points per 10-year increase in driver age. The interaction between age and system implementation, interaction between age and modality, and interaction between age, system implementation, and modality on the percentage of glances off the forward roadway longer than 2 s were not statistically significant. Mean total eyes off road time and mean off-road glance duration are other metrics used to characterize glance behavior and the distraction potential of embedded interfaces (e.g., NHTSA, 2013). These metrics provide similar information

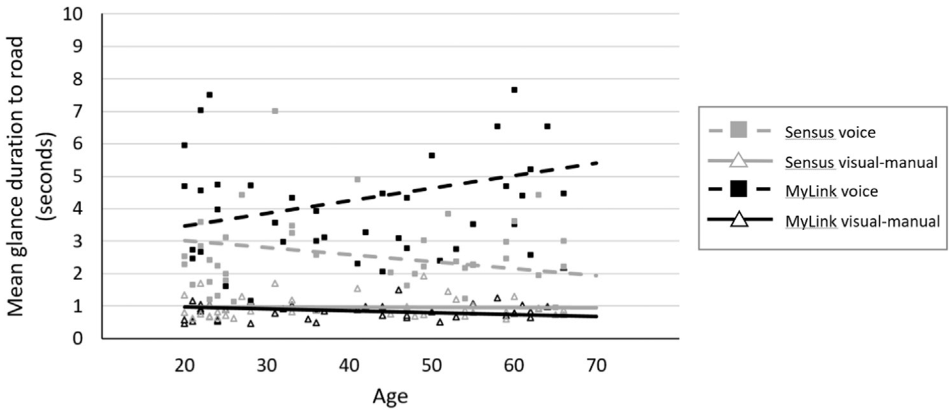

Fig. 2. Mean duration of a single glance to forward road when phone contact calling by age, interface modality, and system implementation. Lines of best fit indicate simple effects of age for each interface modality-system implementation condition. Points reflect a participant's glance duration to the forward road averaged across four phone calling tasks for each modality-system condition.

to those reported in this paper so they are not discussed; however, because total eyes off road time and off-road glance duration are commonly used by researchers, the effects of age, vehicle, and modality on these measures were analyzed, and the model results are reported in Appendix A.

3.2.4. Self-reported workload

The three-way interaction between age, system implementation, and interface modality on driver ratings of workload was statistically significant (Table 3). Self-reported workload ratings of using the visual-manual systems to call a contact (MyLink: $M = 4.74$, SD = 2.56; Sensus: $M = 5.77$, SD = 2.73) were greater than ratings for the voice interfaces (MyLink: $M = 1.86$, SD = 1.86; Sensus: $M = 2.30$, SD = 1.65), but changes in subjective workload ratings by age differed across these interfaces (Fig. 3). For every 10-year increase in age, subjective workload ratings increased 0.1 points for the Sensus voice interface, 0.2 points for the Sensus visual-manual interface, and 0.3 points for the MyLink voice interface. In contrast, ratings of workload decreased 0.1 points per 10-year increase in age for calling a contact using the MyLink visual-manual interface. The main effect of age, the interaction between age and system implementation, and the interaction between age and modality on self-reported workload were not significant.

3.2.5. Task completion time

Driver age was found to significantly affect task completion time (Table 3). Task completion time increased by 3.7 s per 10-year increase in age after holding all other variables constant. The interactions between driver age and system implementation and interaction between driver age and modality on task completion time were not statistically significant, but the interaction between driver age, system implementation, and interface modality approached significance. Younger drivers had faster task completion times when using the Sensus visual-manual interface compared with the Sensus voice interface (Fig. 4). Conversely, younger drivers had slower task completion times with MyLink's visual-manual interface than its voice interface. Task completion time increased with age for the four interfaces at different rates, such that task completion times among older drivers did not vary by the interface modalities for either system. For example, when holding all other effects constant, a 20-year-old driver was predicted to complete the contact calling task 9 s faster using the Sensus visual-manual interface compared with the Sensus voice interface and 7 s faster using the MyLink voice interface relative to the MyLink visual-manual interface. In contrast, a 60-year-old was predicted to complete the contact calling task in approximately the same amount of time when using the Sensus voice interface and Sensus visual-manual interface, and only complete it 2 s faster when using the MyLink voice interface compared with the MyLink visual-manual interface.

3.2.6. Steering wheel reversals per minute

The interaction between driver age and interface modality was significant (Table 3). Overall, the number of steering wheel reversals per minute increased by 0.3 reversals/minute per 10-year increase in age, and this increase was associated with calls ~~were~~ placed using the MyLink or Sensus visual-manual interface (Fig. 5). The rate of steering reversals slightly decreased per 10-year increase in driver age when calls were placed with either voice interface. Fig. 5 displays the number of major steering wheel reversals per minute for each system by modality condition because of the large difference between the two vehicles. The differences between the MyLink and Sensus were likely due to inherent characteristics in CAN-Bus data and handling of the two vehicles. The main effect of driver age, and interactions between driver age and system implementation and interaction between driver age, system implementation, and interface modality were not significant.

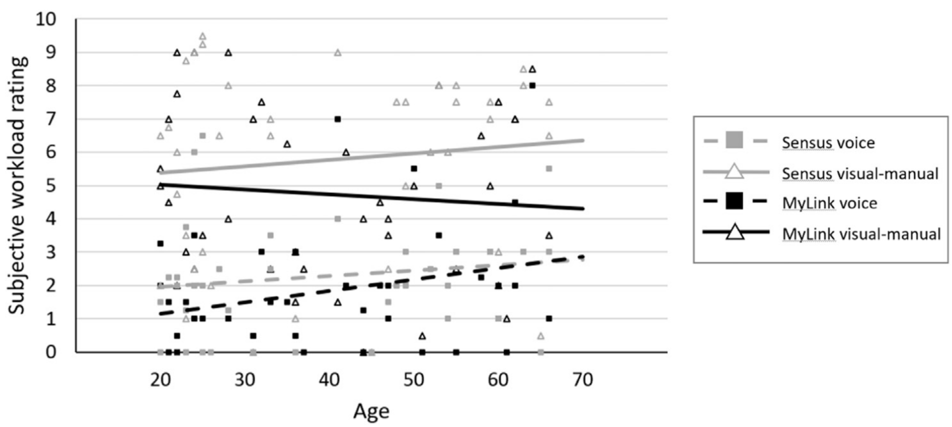

Fig. 3. Self-reported workload ratings as a function of system implementation, interface modality, and driver age. Lines of best fit indicate simple effects of system implementation and interface modality by age.

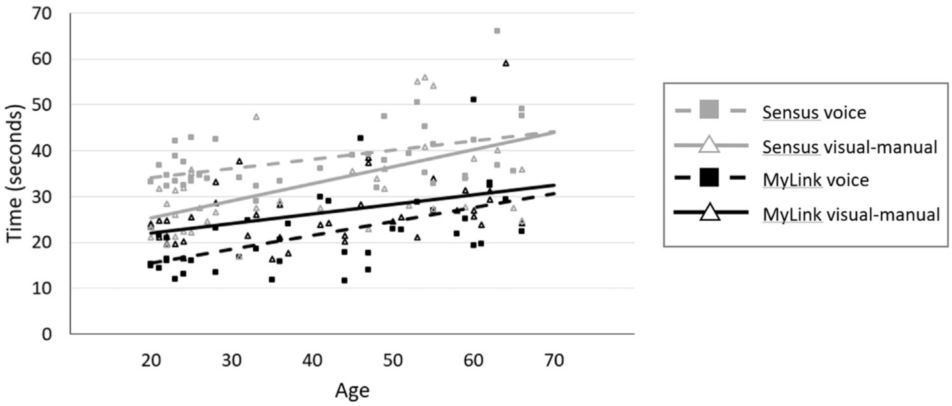

Fig. 4. Task completion times by age, interface modality, and system implementation. Lines of best fit indicate simple effects of age for each interface modality-system implementation condition. Points reflect a participant's completion time averaged across four phone calling tasks for each modality-system condition.

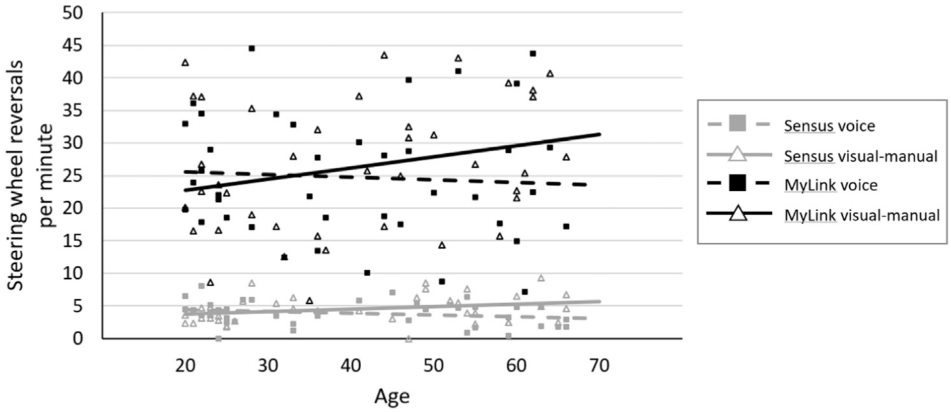

Fig. 5. Steering wheel reversals per minute by driver age and interface modality. Lines of best fit indicate simple effects of age for each interface modality-system implementation condition. Points reflect a participant's mean wheel reversals per minute during four phone contact calling tasks per modality for assigned system implementation.

4. Discussion

Previous research has found that using the voice interface of an infotainment system embedded in the vehicle to place a call while driving reduces the extent the driver's visual attention is drawn away from the road relative to when using a visual-manual interface, and that some voice-interface designs are more successful than others at reducing the visual demand of visual-manual interfaces (Mehler et al., 2016). The current study extends these findings by demonstrating that voice interfaces are not as visually demanding as visual-manual interfaces for drivers of all ages (e.g., McWilliams et al., 2015; Tijerina et al., 2000; Tsimhoni et al., 2002; Wikman & Summala, 2005), and the MyLink voice interface enhanced visual attention to the forward road compared with the visual-manual interfaces and more than the Sensus voice interface for drivers of all ages for the phone contact calling activity. The mean percentage of time each driver looked at the forward road when calling a contact was constant across the age range for drivers who used Chevrolet MyLink's "one-shot" voice interface but decreased as driver age increased when the visual-manual interface was used. In contrast, the percent of time drivers looked at the forward roadway when using the Sensus menu-based voice interface was greater than when they used the visual-manual interface; however, the percentage decreased at a faster rate per 10-year increase in driver age when drivers used the voice interface compared with the visual-manual interface. Likewise, the average duration of glances to the forward road were longer when drivers used either voice interface relative to the visual-manual interface, but among drivers who used the MyLink voice interface the average glance duration increased with driver age, whereas it decreased with driver age for drivers who used the Sensus voice interface.

These interactions between age, interface modality, and system implementation add further insight into how different design approaches impact driver attentional load, particularly with respect to the voice interfaces. The menu-based Sensus voice interface required more driver inputs (Reagan & Kidd, 2013), leading to longer task completion times than the one-shot MyLink voice interface when controlling for age as reported in Mehler et al. (2016). The Sensus voice interface, but not MyLink, also included commands directing the driver to select options and confirm selections from a list on the center stack display that inherently directed drivers' visual attention away from the forward road. As described above, these aspects of the menu-based implementation likely contributed to the age-related reductions in visual attention to the forward roadway for drivers using the Sensus voice interface. Conversely, the one-shot approach implemented with MyLink's voice interface enhanced the amount of time drivers of all ages looked at the forward road when calling a contact.

It is interesting to note that the mean percentage of glance time that drivers looked to the road when calling a contact with MyLink's one-shot voice system was similar to percentages reported in previous studies of eye glance behavior in naturalistic settings when drivers were not required to engage in secondary behaviors. Tijerina, Barickman, and Mazzae (2004) study of car following found that drivers looked at the forward road 86% of the time in conditions when time headways were 1.9 s, on average (see also Farmer et al., 2015; Tivesten, Morando, & Victor, 2015). However, the current finding could also be associated with increased gaze concentration when completing cognitively demanding secondary tasks (Recarte & Nunes, 2000; Reimer, Mehler, Wang, & Coughlin, 2012). The net impact of such gaze concentration on actual crash risk, if any, has not been established.

In contrast to findings discussed above, the results for task completion time and percentage of off-road glances longer than two seconds suggest an age-related increase in attentional demand during engagement with in-vehicle devices regardless of interface modality or design considerations. These main effects are consistent with previous work showing a general decline in performance that is related to reduced cognitive function inherent in aging (Lee et al., 2015; Strayer, Cooper, Turrill, Coleman, & Hopman, 2015) and indicate that interface design and modality cannot completely eliminate age-related declines in performance.

Familiarity with using technology in general or with using electronics while driving may also contribute to attentional demand associated with placing phone calls. Guo et al. (2016) reported that cellphone use during naturalistic driving was most prevalent among 16–20 and 21–29-year-old drivers. Although there was a high accuracy rate for the phone calling task, Table 2 shows higher error rates for the three older age groups compared with the 20–24-year-old age group. Future research could examine interactions between familiarity with using technology, attentional demand, and age, but it is unlikely that the higher error rates for 25–39 year-olds compared with 20–24 year-olds was due to cognitive aging.

In general, drivers' self-reported workload when using the voice interface of either system was much lower than the workload ratings for using either visual-manual interface, and workload ratings increased with age for both voice interfaces and the Sensus visual-manual interface. However, the workload ratings for the MyLink visual-manual interface did not follow this trend and decreased as driver age increased. A difference between the two visual-manual interfaces was that Sensus presented all contacts in a single alphabetized list, which required repeated turns of the rotary knob, whereas MyLink used submenus that reduced the number of rotary knob turns by constraining the contact list into smaller bins. Older drivers may have found the repeated turns required by Sensus more demanding and MyLink's sub-menus easier to search, relative to younger drivers. Indeed, a study of in-vehicle visual displays by Burnett, Lawson, Donkir, and Kuriyagawa (2013) found that a wide and shallow menu structure had lower demand costs than narrow and deep menus when the items were in alphabetical order as was the case with both visual-manual menus tested in the current study. The lack of age differences in self-reported workload between the two voice interfaces relative to measures of visual attention may be due to system-specific design considerations, the nature of self-report, and the overall demand of the phone contact calling task. The Sensus may have received the lower ratings for the use of brief commands, slow pacing, system prompts, and error recovery and prevention, whereas MyLink's compound commands and streamlined task structure lowered demand relative to its visual-manual system. Participants' high task completion accuracy may also have contributed to the low self-reported workload ratings of both voice interfaces.

The increase in steering wheel reversal rate with age when drivers called a contact using the Sensus or MyLink visual-manual interfaces and not the systems' voice interfaces is consistent with previous research that suggests a relatively higher demand for older drivers than younger drivers in lateral vehicle control when completing visually demanding in-vehicle secondary tasks. For example, Tijerina et al. (2000) noted a significantly higher rate of lane excursions per trial for older drivers compared with younger drivers when they entered destinations into four different navigation interfaces, but lane excursions were limited to the three visual-manual interfaces. Wikman and Summala (2005) reported increased lateral displacement for older relative to younger drivers when completing visual search tasks that required either manual or vocal responses. The current findings likely reflect the increased visual attention to the forward road that both voice interfaces afforded relative to their respective visual-manual interfaces.

4.1. Limitations

The large differences in steering wheel reversal rate between vehicles were likely unrelated to driver performance and due to differences in the way this information was reported on the vehicle CAN bus and differences in vehicle handling characteristics. Unfortunately, this meant that steering wheel reversal rate could not be compared between vehicles; however, the differences in steering wheel reversal rate observed between the voice and visual-manual contact calling task trials within each vehicle are consistent with previous research (Wikman & Summala, 2005; Tijerina et al., 2002), showing decreased lateral control with age when drivers are engaged with in-vehicle secondary tasks, particularly those with heavier visual demand. A more important consideration is that the age range in the current study excluded teen drivers and those older than 66, and it would be worthwhile to measure the effects of different interface design approaches on these drivers. The current study also administered secondary tasks in a forced-paced manner, although participants were instructed to prioritize safety and skip tasks if they did not feel they could complete them safely. Observational data suggests older drivers limit exposure, although not completely, to electronic device use while driving, and driver willingness to engage in secondary behaviors is dependent on contextual factors such as traffic complexity (e.g. AAA Foundation for Traffic Safety, 2016; Kidd et al., 2016).

4.2. Conclusion

Naturalistic driving research has shown greater increases in crash risk for younger and older drivers relative to middle age drivers when engaged in visual-manual cellphone interactions (Guo et al., 2016). The current findings highlight how embedded voice interfaces with different design approaches might reduce attentional demand when drivers of different ages interact with the systems. The structured menu-based approach implemented with the Sensus voice system increased visual attention to the forward roadway for all drivers relative to both visual-manual interfaces, but the percentage of glances and mean duration of single glances to the forward road diminished with increases in age. In contrast, visual attention to the forward roadway for the one-shot MyLink voice interface was constant (percentage of glances) or increased (mean glance duration) across the age range. The benefits associated with MyLink's one-shot voice interface are compelling given the many physical, cognitive, and sensory/perceptual changes associated with aging (e.g., Karthaus & Falkenstein, 2016). However, it is important to underscore that despite the increased visual attention to the forward roadway associated with the voice interfaces, older drivers demonstrated increases in other measures of attentional demand across the implementations studied here.

Acknowledgements

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Appendix A

See Figs. A1, A2 and Table A1.

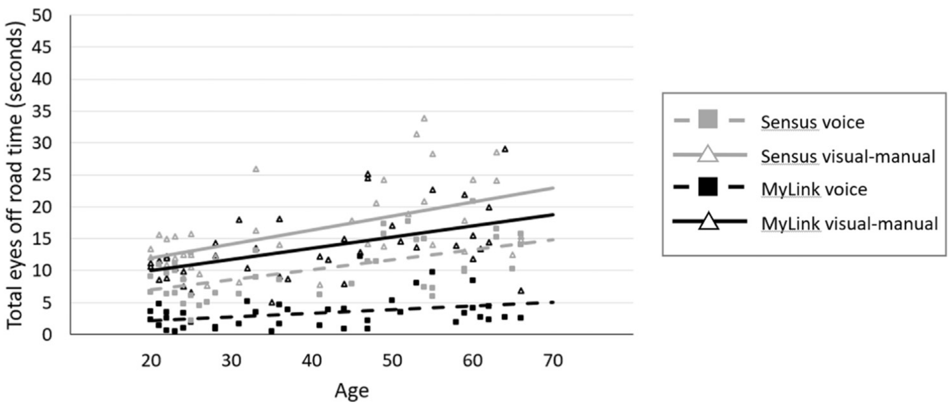

Fig. A1. Total eyes off road time by age, interface modality, and system implementation. Lines of best fit indicate simple effects of age for each interface modality-system implementation condition. Points reflect a participant's eyes off road time averaged across four calling tasks per modality-system condition.

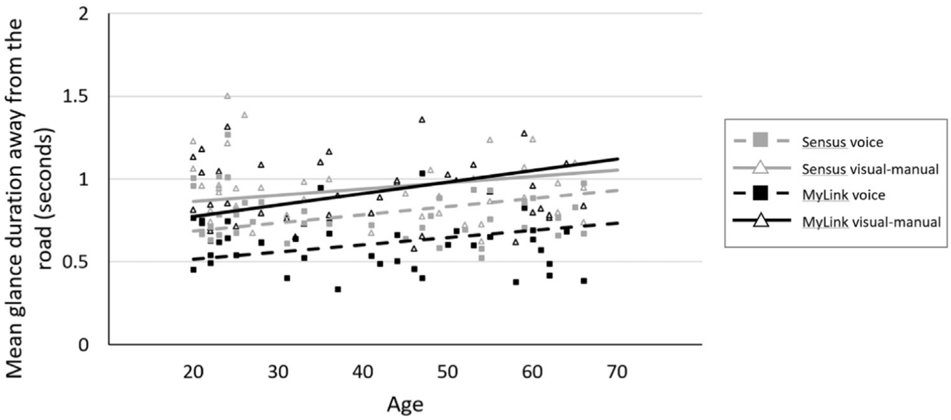

Fig. A2. Mean off-road glance duration by age, interface modality, and system implementation. Lines of best fit indicate simple effects of age for each interface modality-system implementation condition. Points reflect a participant's glances off the forward road averaged across four calling tasks per modality-system condition.

Table A1
Summary of main effect of age and interactions of age with system implementation and interface modality for total time eyes off forward road and mean duration of off-road glances.

Dependent Measure (variable in data)	Type III *F*-test			
	Age	Age × System	Age × Modality	Age × Modality × System
Total time eyes off forward road	$F(1, 76) = 38.63$, $p < 0.001$	$F(1, 76) = 2.18$, $p = 0.14$	$F(1, 556) = 6.27$, $p < 0.05$	$F(1, 556) = 0.57$, $p = 0.45$
Mean duration of single glance off forward road	$F(1, 76) = 23.94$, $p < 0.001$	$F(1, 76) = 0.37$, $p = 0.54$	$F(1, 556) = 0.98$, $p = 0.32$	$F(1, 556) = 6.16$, $p < 0.05$

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2018.10.020.

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